

HUMAN RESPONSE TO EXPLOSION-INDUCED NOISE AND VIBRATIONS

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ABSTRACT

Performance evaluation of missiles and small ammunition is usually associated with explosions in which detonation is initiated above or below ground within previously approved test ranges. The magnitude of induced vibrations and noise from these sources are usually difficult to identify and are unconsciously registered as disturbing by the human perceptive system. In addition, the induced vibration may cause damage to nearby structures, which can result in expensive law suits. With the growth of population and encroachment of civilian neighborhoods onto military test sites, the requirements to condition and control levels of noise and vibrations become more stringent. Similar situations also arise during construction of tunnels or other infrastructures in which explosives are used for excavation in urban areas. Within the test sites, the peak magnitudes of noise and vibrations that can be tolerated by military personnel are usually much higher than those for civilians in urban areas. This paper provides an insight into assessment of human response to explosion-induced noise and vibrations by considering both military and civilian requirements. These requirements are used to develop a method to determine the maximum TNT equivalent weight of explosives that can be detonated at a given site without causing annoyance of civilian population. Also, this paper highlights the importance of the site specific ground conditions on blast-induced vibrations.

1. INTRODUCTION

The principal hazardous effects of explosives event are airblast pressure, ground shock, fragments, thermal and chemical hazards. Such hazardous outputs are generally produced following an explosive detonation in the military and construction industries. Thermal and chemical products of explosion have been studied extensively. Data on blast-induced fragments associated with accidental detonation in military installations are limited in scope to those documented from recent tests by the US and foreign military agencies (Bakhtar, 1996). Environmental impacts of airblast pressure and ground shock have been documented in the DOD 6055.9-STD and NATO AASTP-1. Many empirical formulas has been proposed for prediction of airblast and ground shock originating from a potentially explosive site (PES). However, in almost all the formulations reported the site specific characteristics of the ground or those of the engineered systems are not well defined. Depending on distance from a source, the airblast and ground shock can directly effect the human perception in terms of noise and vibration. Human annoyance to blast-induced vibration was studied in Germany as early as 1930s (Reiher and Meiser, 1931) and several research program on the subject was initiated in the United States, by the US Bureau of Mines, in 1950s (Jenkins, 1956). This paper further discusses blast-induced vibration and elaborates on the influence of the site specific ground characteristics on the human perception to such events.

2. HUMAN RESPONSE

In the United States, extensive Studies have been carried out by the U.S. Bureau of Mines (Siskind et al., 1980) concerning the structural damage from blast-induced vibrations and to establish the damage criteria. The U.S. Bureau of Mines recommendations for the ground vibrations and are shown in Figure 1. In an earlier study, Siskind (1973) reported a vibration level of 2 inch-per-second (ips) of the “ground motion velocity,” or “peak particle velocity” (PPV) as the point of separation between the safe zone and the zone of damage. The PPV of 2 ips has been accepted as the upper bound of vibration for blast design considerations and is being used extensively. However, such an upper bound value does not guarantee that the damage will not occur. In addition to the ground conditions, the method of construction employed for the building, construction material used, type of footings, are all contributing factors to the response experienced by structures.

In Figure 1, the PPV of 0.75 ips is recommended in the frequency range of 4 to 12 Hz when gypsum board is used for interior walls of the building. A lower

A peak particle velocity of 0.5 ips is recommended when plaster cracking can occur. **But how would such amplitude of vibrations effect the human response?** Obviously high level of vibrations can be harmful to the human body. But, such levels of heavy vibrations seldom

occur in buildings. Therefore, what the Contractors may face will be the disturbance effects or better put expectation effects from the owners of the structures.

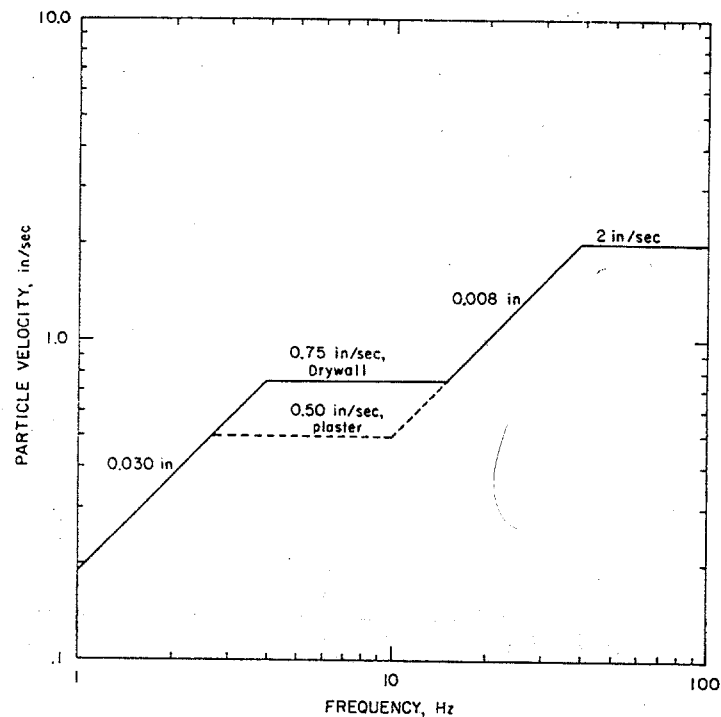
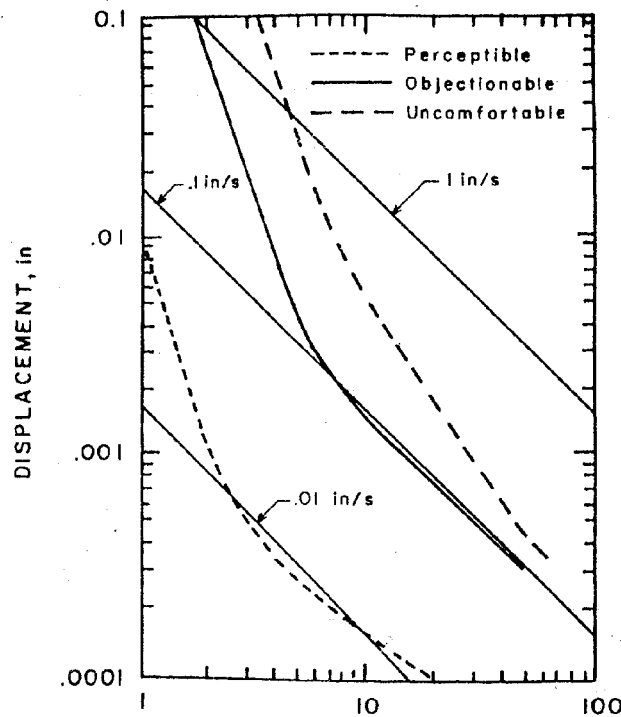


Figure 1. U. S. Bureau of Mines Recommendations for Ground Vibrations.

Results of investigation reported by Reiher and Meiser (1931) and later by Wiss and Parmelee (1974) on the influence of the intensity of vibrations on the degree of human annoyance indicated that the perceptiveness of vibrations is reduced when the exposure time decreases. Prolonged exposure even at PPV of 0.2 ips can cause annoyance in human beings.

Jenkins (1956) discussed the classical studies performed by Reiher and Meiser in the mid 1930s and presented them in graphical form as shown in Figure 2. As shown in Figure 2, in the frequency range associated with the blast vibrations 0.1 ips, the ground motion velocity or PPV is considered objectionable. It must be pointed out that most of the recent studies on vibrations were performed in the mining districts or construction site outside urban areas where higher PPV than what is presented in Figure 2 can be acceptable based on local regulations.

Figure 2. Human Response to Vibrations (Jenkins, 1956).



3. BLASTING

With the growth of population and encroachment of civilian neighborhoods onto military test sites, the requirements to condition and control levels of noise and vibrations become more stringent. Similar situations also arise during construction of tunnels or other infrastructures in which explosives are used for excavation in urban areas. Within the test sites, the peak magnitudes of noise and vibrations that can be tolerated by the military personnel are usually much higher than those for civilians in urban areas. The emphasis for the present discussion is directed towards effects of vibrations on civilian from military or construction related blasting. In the construction industry, explosives are extensively employed for conventional drilling-blasting methods of underground excavation. Tunneling using the **smooth blasting** technique is being commonly practiced in the Nordic countries. It is now becoming a standard practice throughout the North America mainly because it is intended to minimize the blast-induced damage to the surrounding walls of the opening. However, the method was originally developed for the competent rocks, such as the Swedish granite, and in the less competent rockmass variations of the method should be experimented with until the optimum

scheme for the rounds at a given site is established.

For the construction industry or civilian projects there are other stringent requirements, such as compliance with the pre-set levels of vibration and noise on the surface. In order to comply with such requirements, the “round designer” is forced to use a variation of the smooth blasting technique and use primers such as “Magnadet Primary Initiation Scheme” to initiate the charges from a safe distance. Such initiation devices which operate based on “magnetic coupling” concept is widely used in tunneling industry in Europe. In addition of being safer against pre-mature firing from the nearby clutter of electric signals, it is also proven to reduce vibration and noise level. Still, the site specific geological conditions, degree of saturation, charge weight per delay, etc., control the observed effects on the surface. There are usually more than one hole per delay in the production holes. For three holes per delay, depending on tunnel configuration and overburden depth, blast-induced stress waves (ground shocks) are sent to the surface from three separate sources and because of superposition of the stress waves, the induced vibrations on the surface would be greater than a single source, i.e. one hole per delay. This effects can become even more severely amplified, if there is a water table present below the firing level, due to reflection off that layer. The amplitude of the stress wave becomes diminished if there are pockets of partially saturated material above the firing level due to seepage into the working space. Replacement of water filled pore space with air act as a damping media for the stress waves. On the other hand, if the water table is near the source, it can act as an amplifier and increase the amplitude of the stress wave. This phenomena has been clearly demonstrated and discussed by Bakhtar (1989) for wave propagation in anisotropic media. Therefore, in areas where the water table is close to the surface and depth of cover is shallow, it may become necessary to reduce the number of holes per delay to further protect the surface structures and reduce risk of the potential law suits. As a result the construction industry should be prepared to make such adjustments in their blast rounds configurations should the site conditions warrant such changes.

In general, because geologic system, i.e., soil/rock is not an isotropic medium, it is impossible to predict the vibration level at a given distance in the absence of a site characterization methodology. It is well understood that blast-induced stress waves attenuate differently depending on the site specific geologic characteristics of the ground including the water table location. Additional factors include, round configuration, explosives weight and performance, coupling between the explosives and the geologic system (rock), and delay time between each blast round.

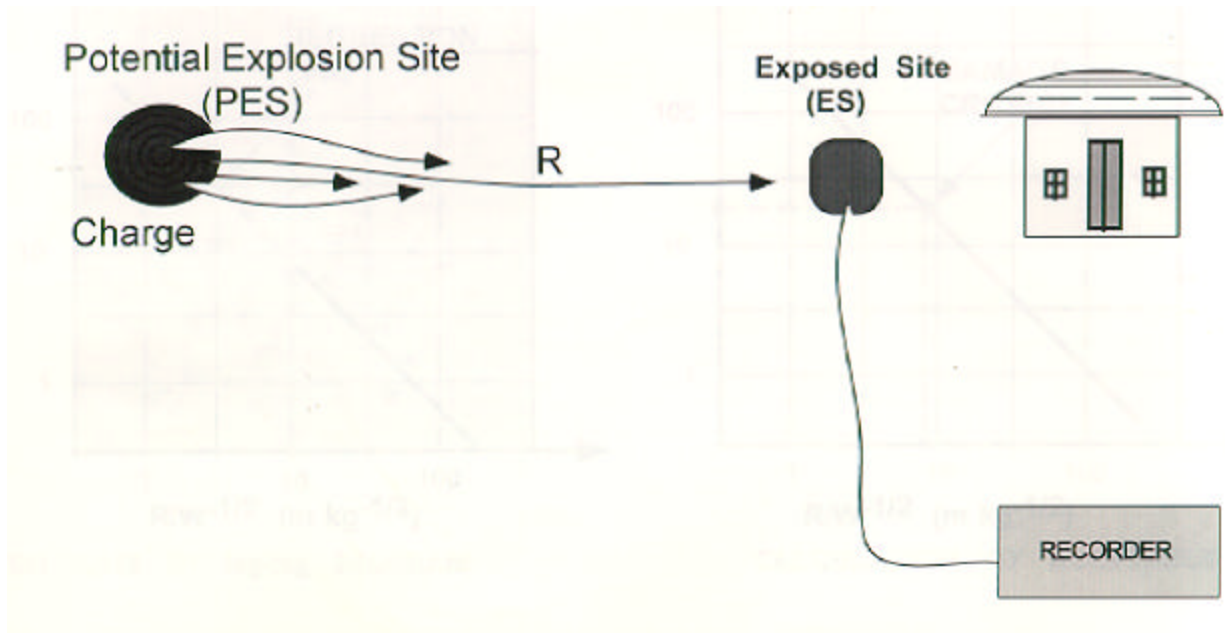
In commercial practice, the maximum particle velocity (inch-per-second or mm-per-second), refer to Figure 1, is used to express maximum vibration level that an object can withstand without being damaged by the blast. The results of many years of investigation reported (Siskind, et al., 1980) show that a usable empirical relationship between particle velocity,

v, weight of charge, W, and the distance R can be represented by

$$v = \frac{K}{\left[\frac{R}{\sqrt{W}} \right]^a}$$

where constants “K” and “a” vary depending on the site conditions, blasting geometry and type of explosives. In order to use the above equation for a reliable prediction of vibration level at a given distance a series of small tests should be conducted as shown in Figure 3. In these tests a series of small explosive charges are set off to determine the transmission or stress wave propagation properties of the geologic system. For such tests, charges used for the experimental blast are placed in line with the object (structure) to be protected. The time history of the vibration (in addition to the acceleration, particle velocity, or displacement) is recorded for further analysis.

FIGURE 3. EXPERIMENTAL BLASTING.



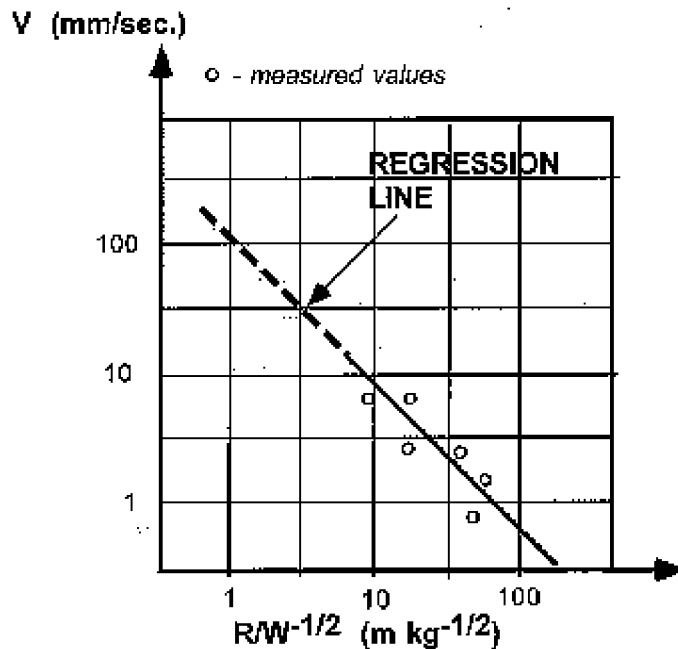


FIGURE 4. PLOT OF EXPERIMENTAL BLAST DATA ON log-log SCALE.

The measured peak values of particle velocity are plotted in log-log scale and a regression line is drawn through the discrete points as shown in Figure 4. As an integral part of risk analysis, maximum vibration level, for neighboring building, equipments, etc., should be determined. This level which may be referred to as the damage criterion, is then put into the diagram in Figure 5. The intersection between the damage criterion and regression line gives the lowest $R/W^{1/2}$ value allowable at that locality.

Although the above method provides a fairly good damage criteria estimation, a computer code which provides real time results for velocities- stresses waveforms, attenuation, and field plots (England and Shimano, 1996) would be by far more appropriate for such analyses. This code which accepts site specific geologic characteristics of the system (including seismic) and developed for ground shock application was employed recently for evaluation of the Los Angeles Metro Rail construction through the Hollywood Hill (Bakhtar and Zimmerman, 1996). For this study, the total weight of the explosives was taken to be 80 kg (176 pounds) detonated simultaneously. Figure 6 shows the attenuation of peak particle velocity with distance from a fully-coupled charge (explosives in contact with the surrounding rock). Note the change in attenuation rate due to the water table and free surface interfaces, a result of rarefaction that occurs as the shock wave impinges upon a lower impedance material. The remaining curve show a fit to the attenuation in the

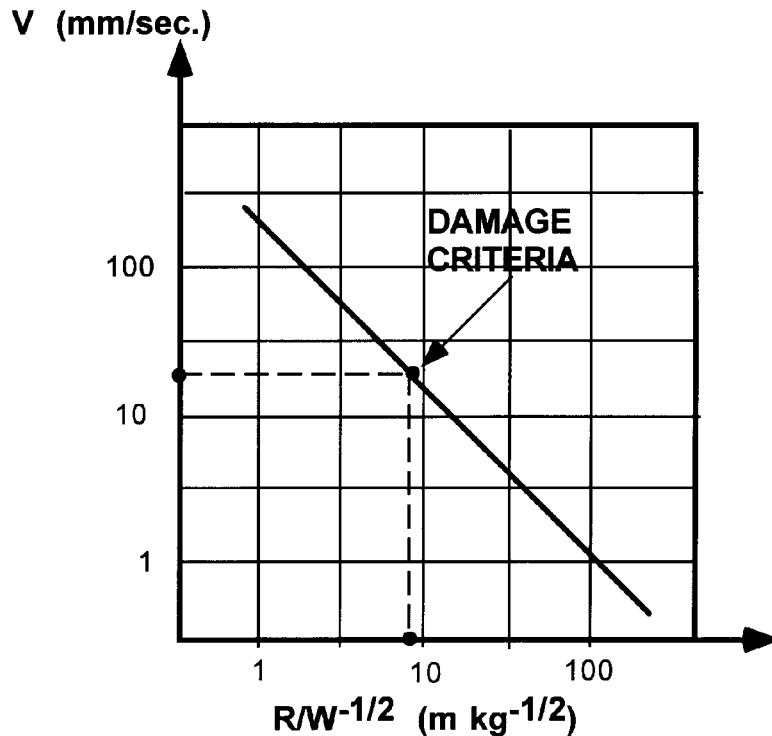


FIGURE 5. DETERMINATION OF LOWEST $R/W^{1/2}$ TO BE USED.

saturated layer, and hydrodynamic or cubed root scaling to other explosive weights. This information was used to adjust the round design.

5. REMARKS

It is cleared that the human perceptiveness of vibrations is reduced when exposure time decreases. Important factors are the frequency of vibrations and exposure time. Also, depending on the observer, human perceptiveness of vibrations can vary.

In practice, it is impossible to define vibration and noise levels for which nobody complains. There is always some percentage of persons in the population who will complain no matter how small the disturbance is. Observers are much more tolerant if the exposure time is small or if they are properly informed of why they must be exposed to the vibrations, how the vibrations would effect them and their property and the exact time of exposure.

For blasting in underground facilities, geologic conditions, degree of saturation, amount of explosives used, configuration of the blast round or purpose of blast, can directly impact the vibration levels on the surface. Although, it is difficult to set threshold values for a

population group, but parametric studies using codes such as the one reported in this study, can be performed to predict an acceptable level. Such calculations can account for site specific geologic conditions to determine the maximum weight of explosives for a given purpose.

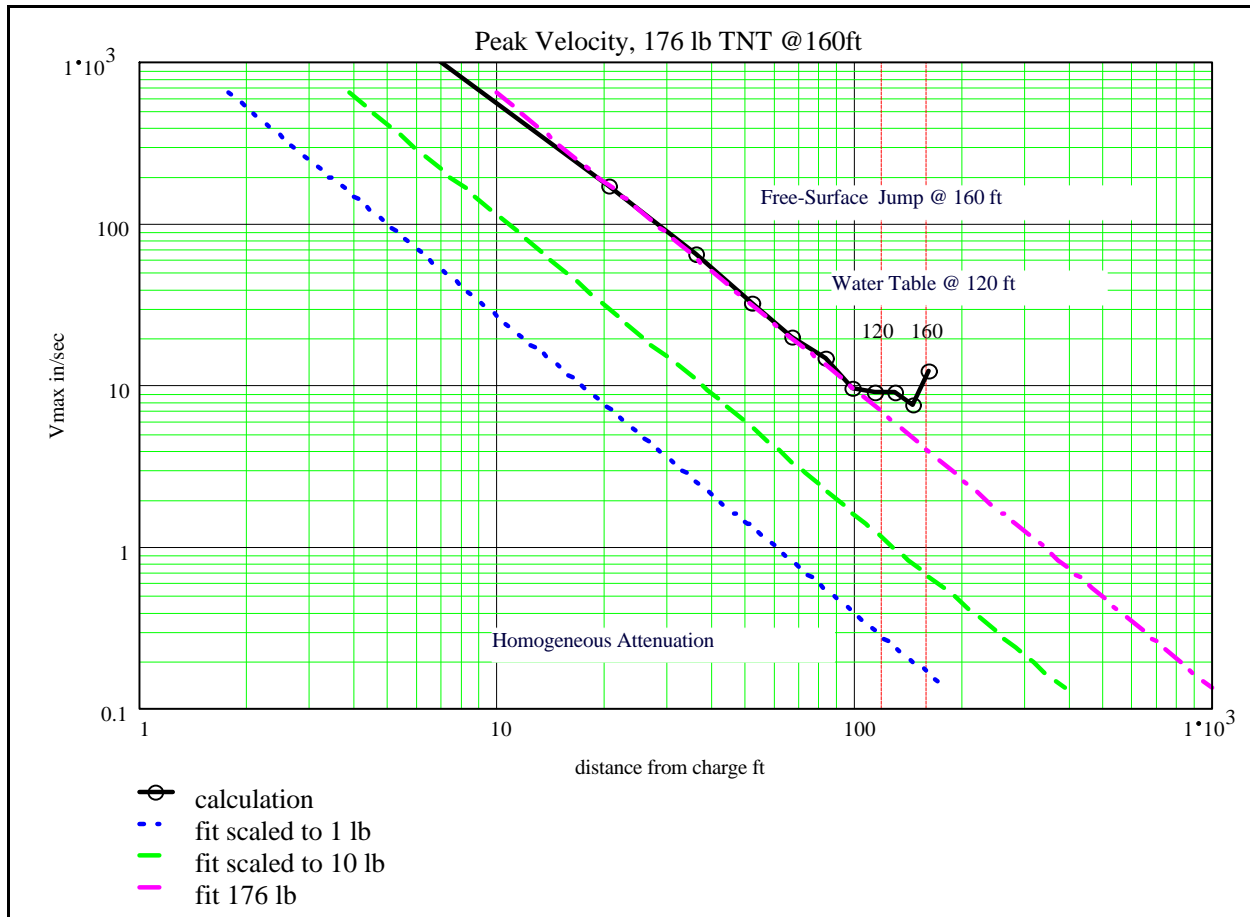


FIGURE 6. GROUND SHOCK CALCULATIONS ON TOPANGA FORMATION (ZIMMERMAN, 1996).

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